Hadron physics at GSI

S. Kox

Synthesis and Consequences of the Workshop : Hadronic Physics at the future GSI Facility

1/ "Non expert" point of view on the antiproton GSI project

Some introductory points about hadronic physics,
the challenges and international context

2/ Discussion about the workshop (along a list of questions)

The antiproton beam, the physics program with
the PANDA detector. Extensions proposed.

2nd International Workshop on the Future Accelerator …

Darmstadt, October 14-17th 2003

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Hadron Physics : Context

Why is this study so important ?

- Understand the strong/color forces and establish its theory (QCD)
  - Nature of confinement. Origin of the mass of quarks.
  - NN and qq forces and the transition between the 2 regimes.
- Understand how nucleons and nuclei are formed from elementary blocks (with quarks and gluons/Nucleon and mesons as degrees of freedom)
- Understand the structure (charge/magnetic moments, spin, …) of fundamental objects like the nucleons
- Hadron physics at the interface between High Energy and Nuclear Physics
- Elementary processes and reactions/decays of hadrons can provide useful results for other fields (SM, QGP, Nucleus, …)

Hadron Physics : Context (II)

Why is there is still so much to do ?

- Particularities of the force between quarks
  - Exchanged gluons carries color and are self-interacting.
  - $\alpha_s \approx 1/2$ at low energies preventing a perturbative treatment (pQCD)
  - quarks/gluons are confined in colorless hadrons.
  - Many body problem and relativist effects to be treated exactly.
- Limitation of previous experiments
  - Beam (energy, intensity, duty cycle, $\delta p/p$, …).
  - Detectors/DAQ (PID, DT, …)
    - ↳ Statistics, systematic errors, S/B ratio
    - ↳ Ambiguities in results
- Absence of exact theory for a long time
  - Non predictive,
    - ↳ Poor guidance for the experiment (pentaquark and sleeping data …)
  - Models with free parameters
    - ↳ Interpretation of results and learning about physics

Hadronic Physics : Challenges

Good progress underway and to come

- Theory and models with physics ingredients
  (Madeleine Soyeur, Ted Barnes, Chris Michael talks)
  - Rapid progress in LQCD with CPU. Discretization (smaller steps), boundary conditions (larger volume), unquenched calculations ($q\bar{q}$ loops).
  - Models (QCD inspired, Chiral symmetry) are used for the light quark sector
    ↳ Predictive level has been/can be further improved
- New generation of accelerators and associated detection set-ups
  - Complete data sets (precision, large energy domain, ...)
  - Unambiguous signatures of states and process with good statistics
- Complementary probes/facilities
  - Possible cross checks and different quantum numbers productions
- Links with companion fields
  - Elementary process for calibration, and change with medium effects
  - Tests for SM, Nuclear Physics, fundamental symmetries (C,P,T)

EM probe : JLab, MAMI, ELSA, GRAAL, SPRING8, …

Form Factors, N*, PV, GDH, Few Body, Transition to pQCD, GPDs, Hypernuclei …

- Energy 1-6 GeV (→ 12 GeV project)
- Electrons and photons

EM probe : HERMES, CERN, SLAC, …

Deep inelastic (SPIN), GPD, SM (PV) …

- Energy 20-200 GeV
- Electrons and muons

Hadronic probe : CELSIUS, COSY, CERN, …

Spectroscopy, elem. cross sections, Hypernuclei, rare decays, …

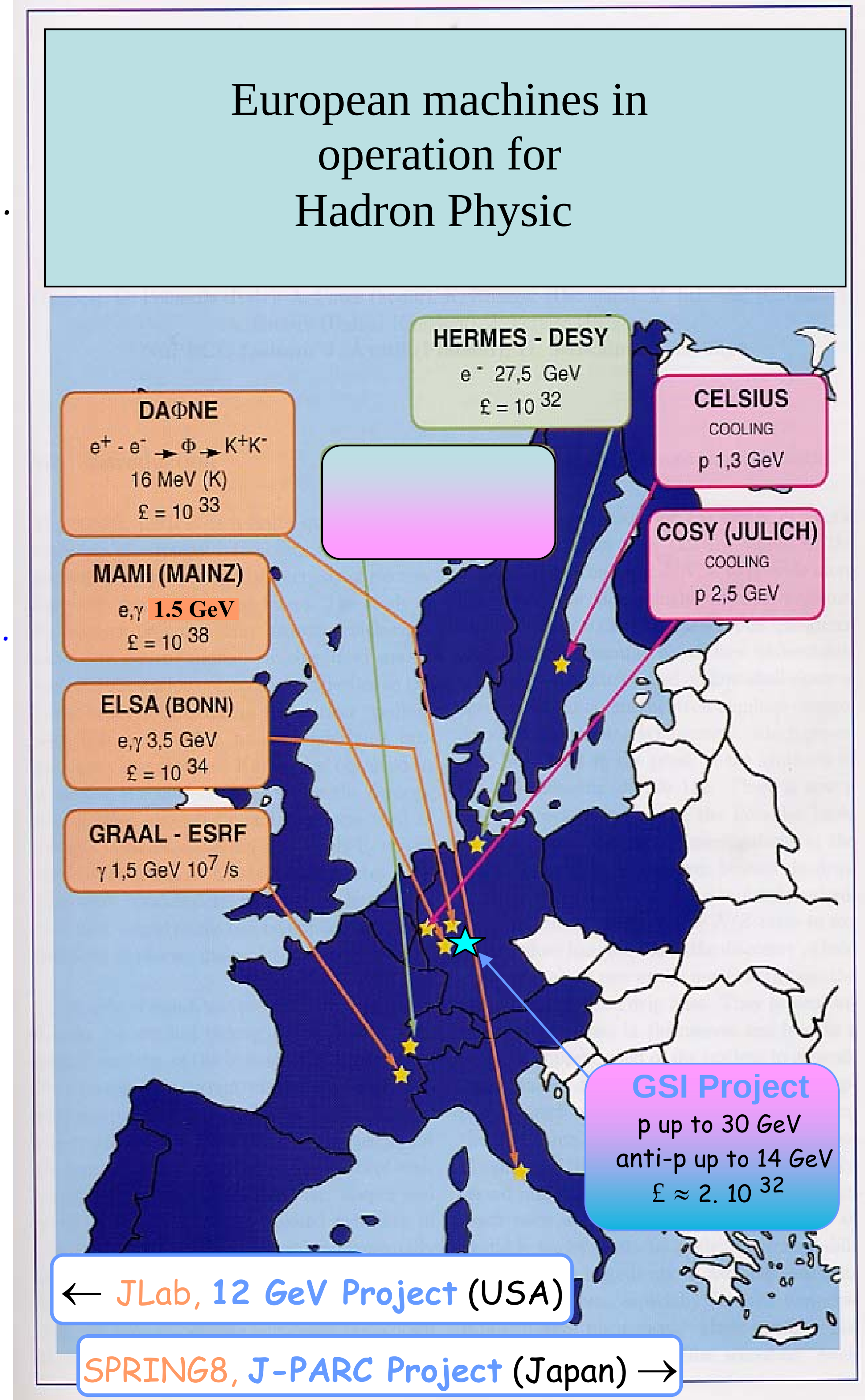
- Energy 1-3 GeV, 200 GeV
- Protons, secondary hadron beams

e^+e^- colliders : DAΦPNE, BEPC, Cornell, ..

Rare decays, Glueballs, spectroscopy…

- CM energy (h-h creation)

Only a few machines still running in 10 years ➔ need new projects



The GSI project and Hadron Physics

How GSI is proceeding

- New GSI facility aimed at
  - Attracting a large community (International coll., Physics cases) ✓
  - Multi-user operation mode. Parallel operation for different physics.
- Provide high quality beams. Here a new probe : antiprotons
  (Norbert Angert, Fritz Nolden, Markus Steck, .. Talks)
  - High energy range in HESR (up to 14.5 GeV, covering the charm sector)
  - Very good resolution (1 MeV to 100 keV, with electron cooling)
  - CW in storage ring and operation stable over 1/2-1h time periods
  - Large intensity (5 10^{11} antiproton in ring) $\leftrightarrow$ $\delta p/p$??

  ⇘ Requires a tricky acceleration scheme (production target and a set of storage rings (acceleration or deceleration) and cooling techniques).
- Large luminosity
  - Internal target (pellet, jets, wire …, t.b.d.). Thickness 2.5 10^{15} cm^{-2}
  - up to 2. 10^{32} $cm^{-2}.s^{-1}$

… but there are requests for more !! (increase production rate/storage ??).

PANDA experimental program (I)

Charmonium
(Klaus Peters talk)

- qq potential
- Regular but also hybrid states (exotic J^{PC})
- Narrow states, but not at full beam energy (resolution less problematic)
- Tests of recent observation. Improved statistics.
  - ↳ Could be used for/during commissioning period

Search for hybrid mesons in charm sector

- Role of the gluon. Flux tube and confinement (scalar/ vector)
- Lower density/mixing of states (also system of 2 heavier quarks)
- Formation versus production could sign directly the J^{PC}
- Large statistics should allow complete partial wave analysis
- Scan in energy over threshold regions to disentangle mixed contributions

Search for glueballs

- Test case for gluonic degree of freedom in theory
- Gluons are naturally well produced in p*p* annihilation

… and more/surprises (multiquarks configurations ??)

Experimental program with PANDA (II)

Hypernucleus

(Alessandro Feliciello talk)

- S=-1
  - Tests of nuclear structure. Study of medium effects
- New perspectives
  - S=-2 (double hypernuclei)
    - Potential Y-N (Pentaquark : N-K) and Y-Y interaction. *H* particle
    - Possible test of weak interaction (Non-PV part)
  - γ spectroscopy (good precision (keV range))
- Strong experimental requirements and adaptations of PANDA
  - Initial wire and secondary nuclear active targets
  - γ detection (background, insertion in PANDA)

Medium effects

- Propagation of J/Ψ in medium (related to QGP)
- Chiral symmetry restoration in dense medium (see CBM)

Questions asked (II) :

1) What detector for this program ?

- Resolution allowing unambiguous determination for states/reaction …
  - Decay products (neutral and charged (B magnet))
  - Partial wave analysis (ϕ dependence)
- Importance of internal target (density, Nucleon and nuclear)

  ↳ Need to make technical choice (pellet/jet, beam cooling issue ??)
- Versatility (covering present Physics cases … and more)
  - Possibility to add specific detectors (γ, targets and vertex, …)
- Choice of level trigger (needed for 4π coverage and large luminosity)
  - Allow various physics programs in parallel

  ↳ PANDA (still under simulation) is developed along those requirements
- Handled/supported by a large (young/2 years old) collaboration

  ↳ PANDA Proto-collaboration : > 200 physicists (42 labs, 15 countries …)

Questions asked (I) :

2) What are the crucial problem (s) in hadronic physics that will likely be not fully solved within the next 10 years ??

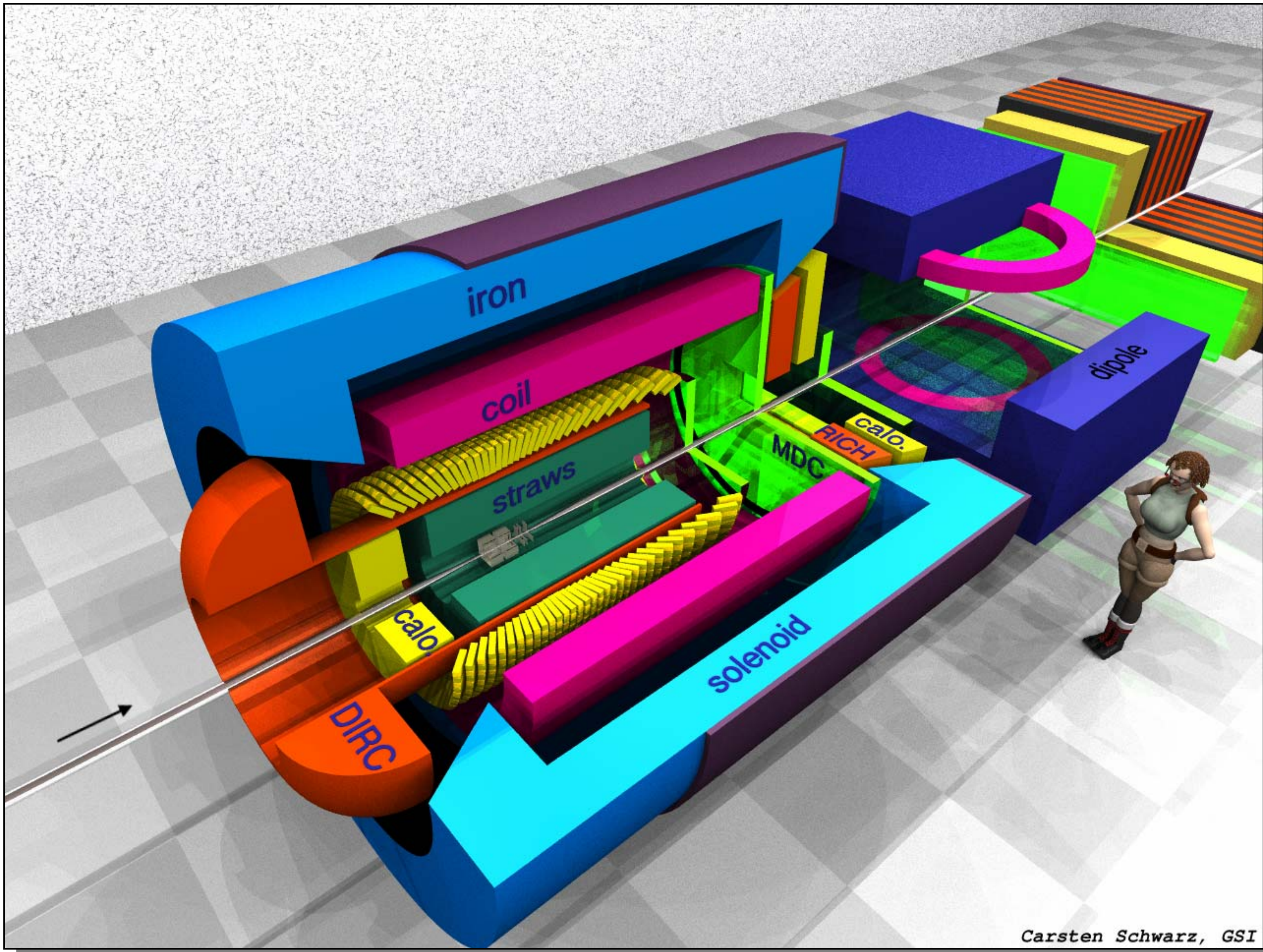
- Full description of hadrons with QCD (theory and experimental tests)
  - Confinement and flux tubes. Excitation of gluonic degree of freedom.
  - Chiral symmetry role/restoration in quark masses.
  - QCD in light quark sector. Role of qq pairs in resonances
  - q-q correlations in nucleon and spin (L_q) issue

3) What type of experiments (or experimental programs) can be done at the future GSI with antiprotons to answer these questions ??

- Discovery of exotic/missing states, glueballs, multiquarks assemblies …
- Detailed/precise spectroscopy of hadrons. Study of charmonium states
- Strangeness in nuclei (S=-1,-2).
- Modification/propagation of meson properties with/in medium (see also CBM).
- Inverse DVCS (luminosity, factorization ??). Nucleon form factor.

⊕ Companion physics :
CP violation, CPT/gravitation, matter distribution and structure in Nucleus, …

PANDA detector



4) Would an existing/future facility do the job ?

- Competition (complementary aspects) from :
  - Halls B/D and JLab 6-12 GeV (exotics mesons, pentaquarks (in s sector))
  - e^+-e^- colliders and upgrades BEPCII+BESIII (charmonium, glueballs, …)
  - B factory via decays processes (charmonium)
  - SPS + COMPASS (charmed baryons, …)
  - J-PARC (Hypernucleus, spectroscopy, …)

GSI beams/experiments can have however several unique features …

- antiproton probe in the high energy range (charm sector)
  - Gluon production. All J^{PC} can be produced.
  - Production of hadrons by pairs. Antiquarks in entrance channel
- E_{pbar} = 0.8 - 14.5 GeV
  - Fine steps in energy for scan (production/formation, threshold)
  - Very good resolution (cooling) down to some 10^{-5} in $\delta p/p$
  - Large intensities of antiprotons (5. 10^{11} in HESR storage ring)
- State of the art PANDA detector and large density internal target

… but announced performances must be fulfilled.

Progress/content/teachings of the Workshop (hadron)

New ideas/programs

- Late night show and intrepid proposals :
  (Paul Kienle, Kurt Killian, Frank Ratmann talks)
  - antiproton-Radioactive beam collider (rms radii of p/n distributions)
  - Polarized target and polarized antiprotons (p$\bar{p}$ scattering)
  - Not shown (to come ??) : How to increase antiproton production rate
- Low energy antiproton program (800 MeV $\rightarrow$ 100 keV)
  (Gerarld Gabrielse , Ryogo Hayano talks)
  - CPT violation with anti-hydrogen. Still a long way to go (traps, laser, ...)
  - antiprotonic atoms (e, m), low energy antiproton cross sections, halo ...
  - More antiprotons needed + NESR + FLAIR + 1-2 decelerating storage rings.
- Not shown in the workshop (see C.D.R. + PANDA internal workshop)
  - CP violation
  - Form factors, inverse DVCS, ...
  - Anti-deuteron formation ((Astroparticle + SUSY, beams ??),

  ⇘ LoI should follow soon and will <u>strengthen even more</u> the physics case

  ⇘ Add a synthesis's of the SM/Fundamental symmetry physics
  which are addressed in several programs

Progress/content/teachings of the Workshop (hadron)

Other ideas/programs in PANDA

- Not shown in the workshop
  (see C.D.R. + new ideas from PANDA internal workshop)
  - CP violation
  - Form factors, inverse DVCS, ...
  - Anti-deuteron formation ((Astroparticle + SUSY, beams ??),

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Other teachings of the Workshop

The machine operation scheme

- More clear (Thanks to pedagogic talks and booklet)
- Allow extensions to lower energies, collider …
- Large luminosity and good resolution
  - An unique production source of antiproton (sharing ??)
  - Strong cooling necessary (duration, choice target, luminosity ??)

The attendance

- > 400 registered, 1/2 from abroad Germany
- Several proto-collaborations :
  - $\approx$ 200-300 physicists, $\approx$ 42 institutions, $\approx$ 15 countries each
- Note that antiproton can/should be a new community of users at GSI !!

Conclusions

The GSI future complex (antiproton beam, PANDA detector, possible extensions) will provide a first class international facility for hadron physics.

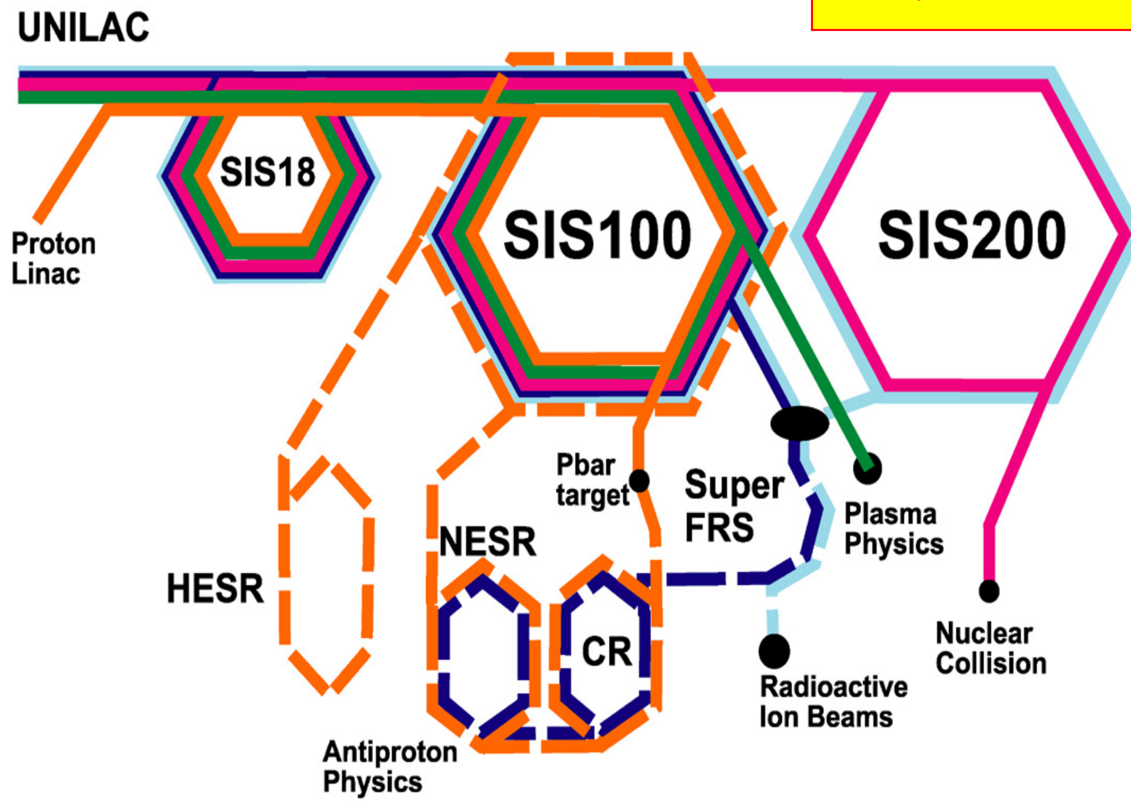
Physics program already attractive and competitive/unique worldwide.
It should provide results in hadron but also in related topics.
Certainly more to come with LoIs.

Congratulation to all people contributing to the tremendous momentum gained to initiate antiproton beams and related physics program @ GSI

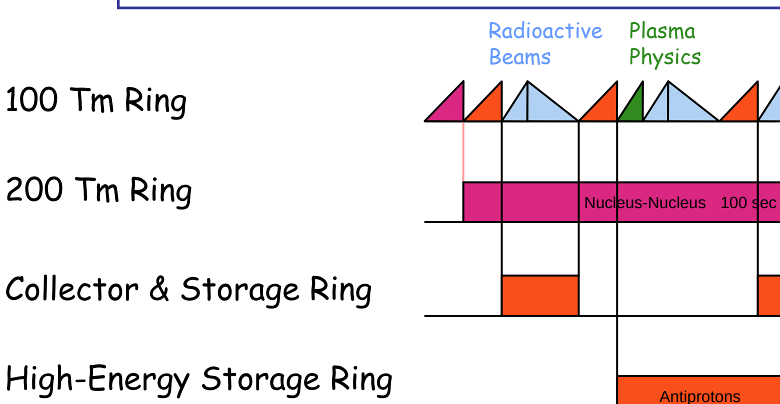
Looking forward for the completion/starting of this impressive project

Good luck – Viel Glück – Bonne chance - …

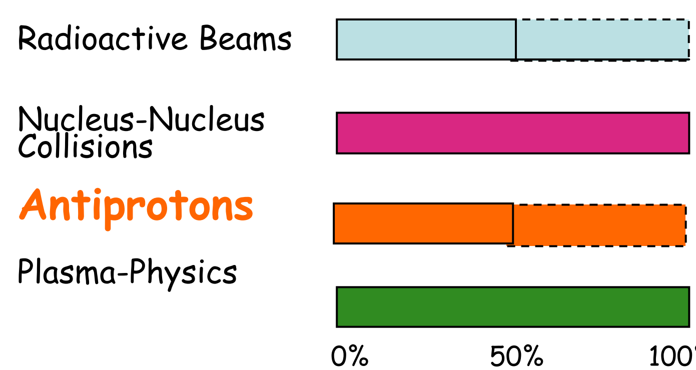
GSI Future Project. Operation Scheme



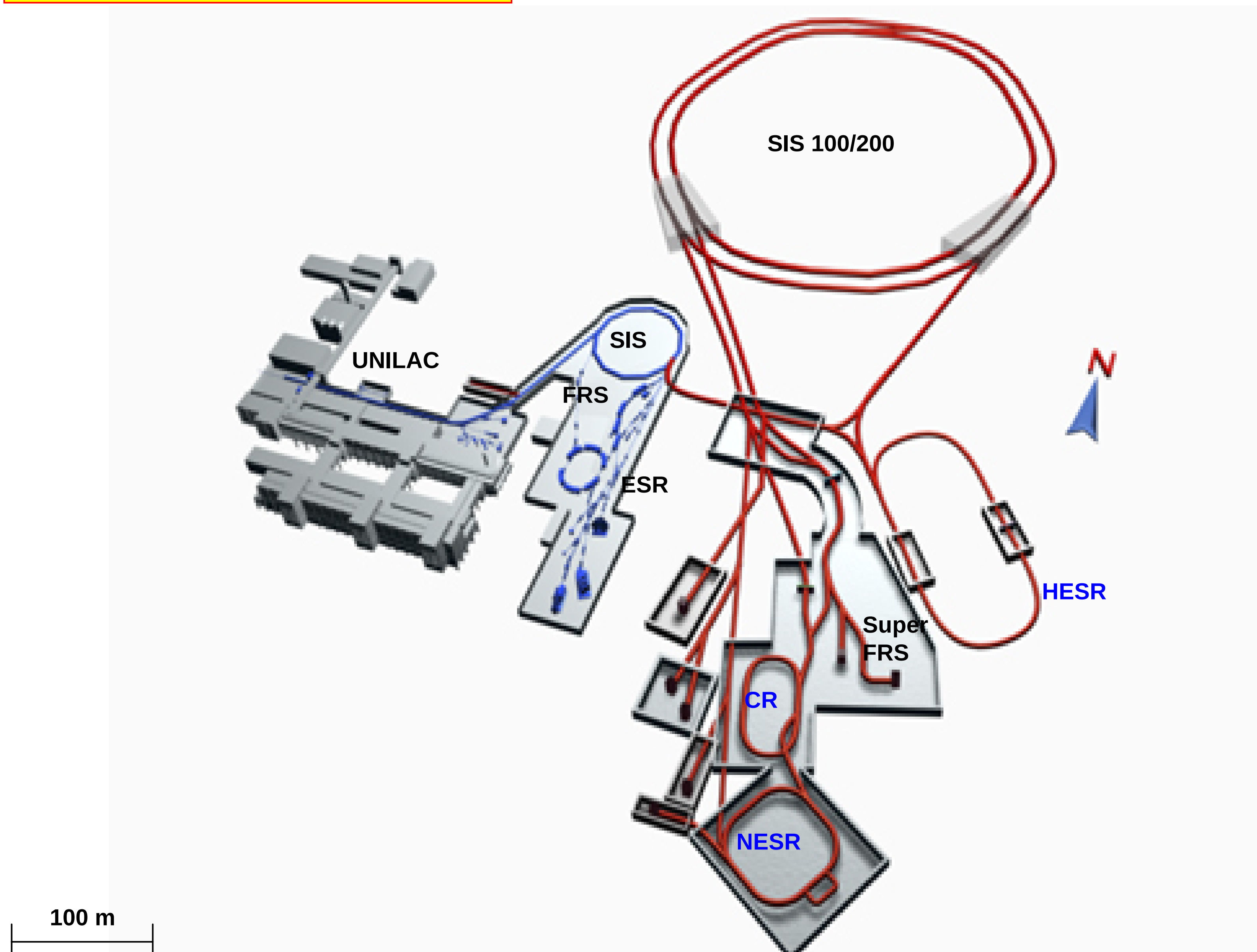
Duty-Cycles of the Accelerator Rings



Duty-Cycles of the Physics Programs



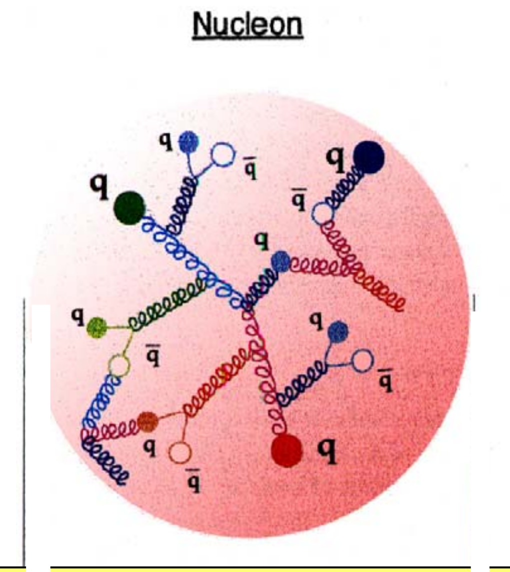
GSI Future Facility
The hadron part



Quark's Structure of the nucleon

Elementary Quarks in interaction

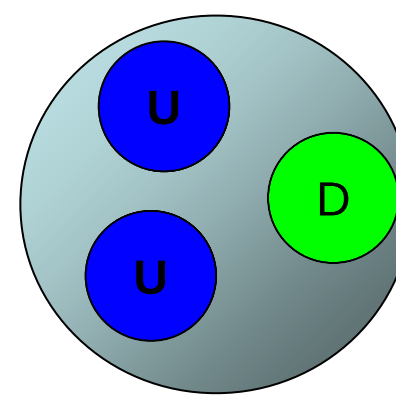
- Growing complexity at low energy
  - Etat fondamental des hadrons !!
- Quarks of QCD
  - proton (938 MeV) = u + u + d (≈15 MeV) + …
    - ↳ Importance of the gluons of the pairs qq
- ☞ Search/study of the contribution of the "sea" (Spin, masse, impulsion, courants …)



$|p\rangle = |uud\rangle + |uudqq\rangle + |uudg\rangle + \dots$

Modèles de quarks constituants

- Dressed Quarks (gluons, pairs qq)
  - Valence Quarks (Charge, spin, quantum numbers)
  - Mass ≈ Mass Hadron/N_{quarks}
- Models of bag
  - Prediction resonances, excited states
  - Models diquarks (missing resonances)
- ☞ Verification : Spectroscopy baryonic/mesonic



$|p\rangle = |u_c u_c d_c\rangle$

From nucleons to nuclei

Elementary force (color)

- quarks et gluons in interaction
  - No analytical treatment of hadron (in non perturbative regime)

NN Interaction

- Nucleons and mesons
- Phenomenological treatment
  - Exchanges of mesons (π,ρ,ω)
- Residual force
  - Screening of color force
- Potential
  - Attractive, vanish at medium range
  - Short range part (repulsive) $\leftrightarrow$ color force

☞ Transition between these different degrees of freedom at large Q^2

Light nuclei : A= 2, 3, 4

- Exact description (3 $\rightarrow$ 4 corps)
- Independents particles
- NN Interactions
  - Different potentials (Paris, Bonn, Argonne ...)
  - MEC (meson exchange currents)
  - Relativistic effects (Kinematics, F.O. nucleon)
  - ☞ Properties of bound nucleons
- NN Correlations, 3-body forces

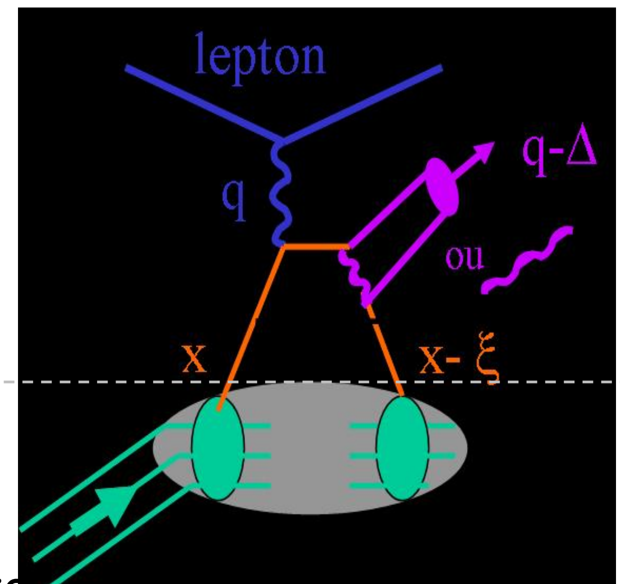
☞ Search for a ¨ standard model ¨ of light nuclei (H, He)

Nuclei and hadronic physics

- NN Correlations
- Chiral symmetry restoration, deconfinement (at high densities)

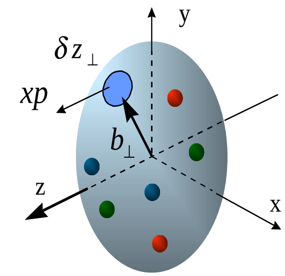
Generalized structure functions

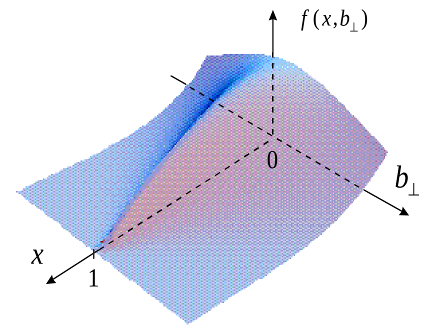
- Function of x, Δ , ξ.
  - ➔ Correlations between partons
- Hard exclusive reactions
  - ➲ Factorization (pQCD regime, to be tested) + handbag diagram

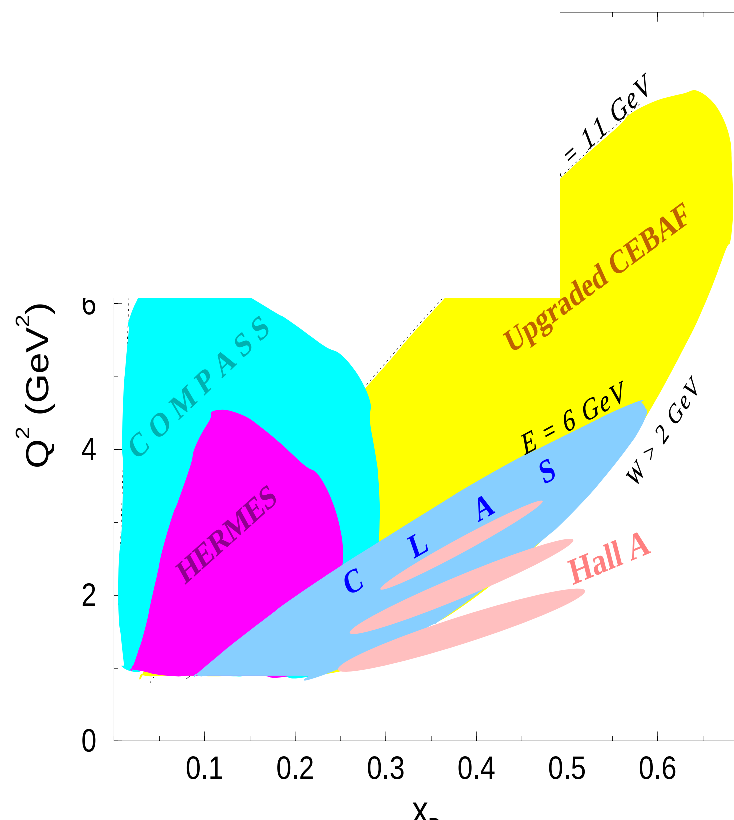


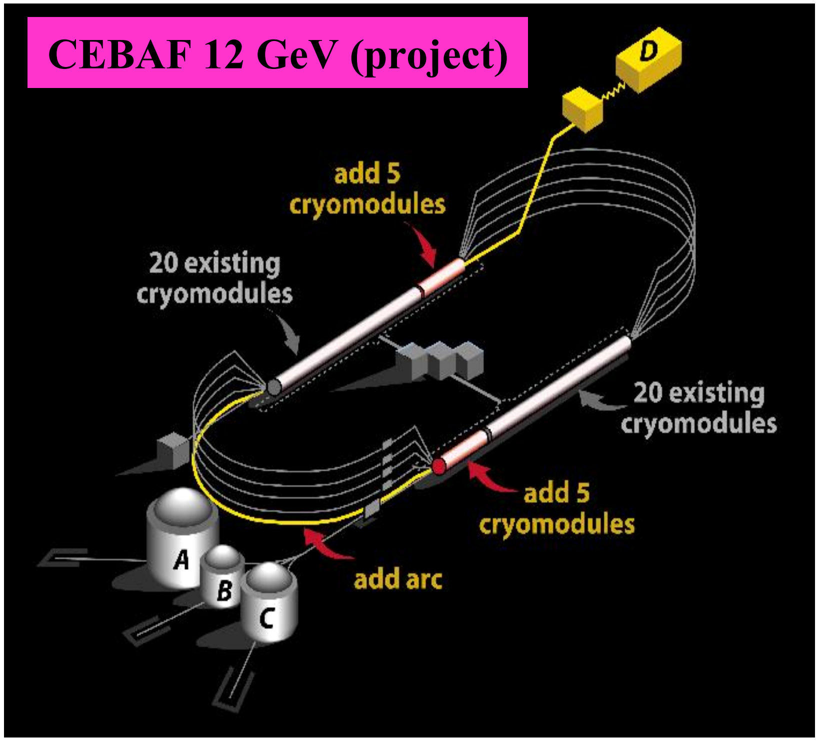
- Integrals of GPDs
  - ➔ Spin of the nucleon (L_q)
- Various kinematical variables
  - ↳ combination of several machines …

- Generalized parton distribution at η=0



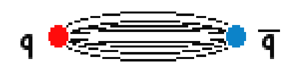






Exotic mesons

- Excitations of flux tube (gluons)



Color field: lines of force.
Because of self-interaction, confining flux tube forms between static color charges

- Hybrid Mesons (new J^{PC})
- Predicted by Lattice QCD
  - ⇒ Confinement ?
- 5 $\frac{1}{2}$ tours (11 GeV)
- New dedicated Hall (D)
  - 4π detector
  - Photons : 8-9 GeV, linear polar.

From energy limitation, restricted to the strange quark sector …

Internal Structure of nucleon and mesons

- EM Form Factors at largest Q^2

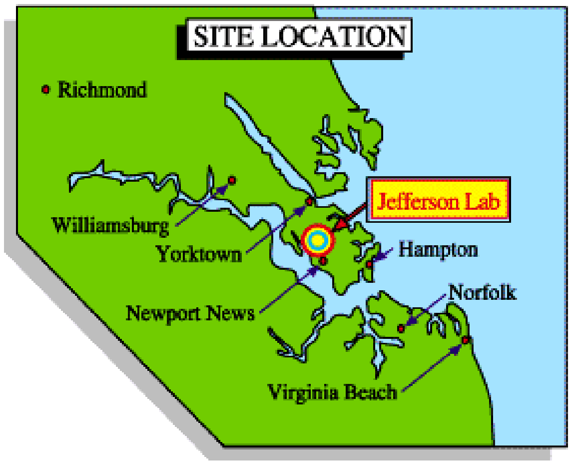
s and c thresholds

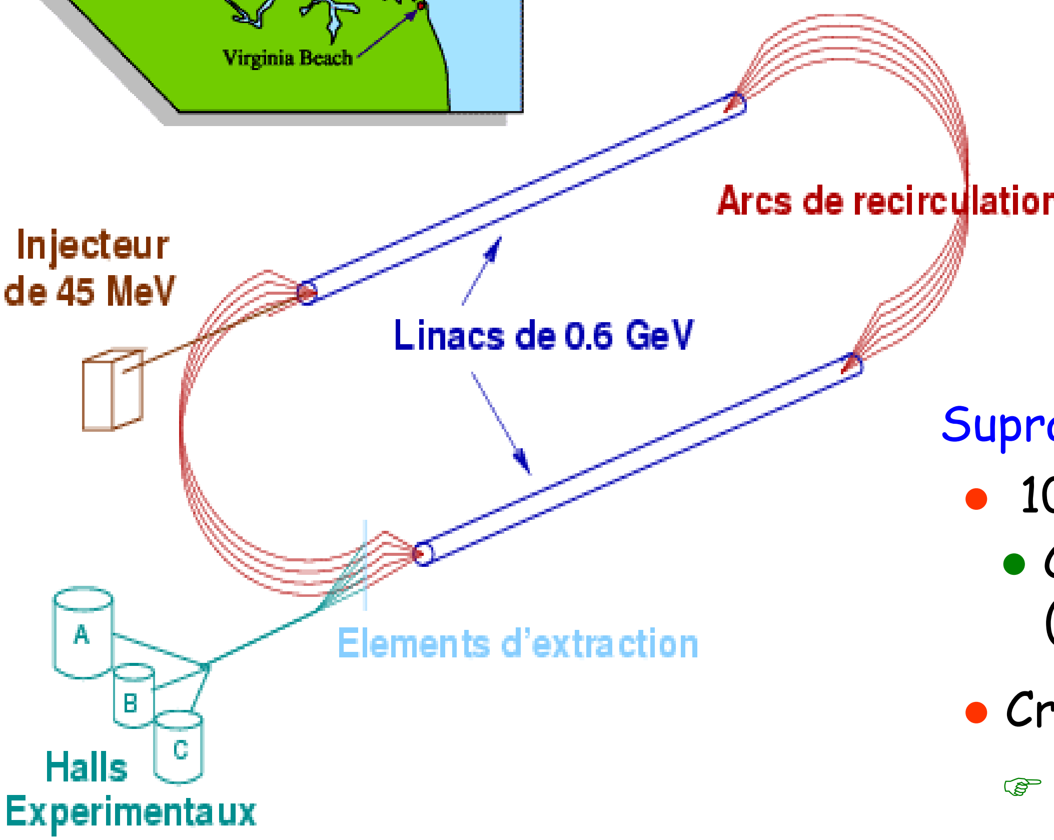
- Photo/Electro-production reactions

Hard scattering reactions

- Structure Functions at large x and Q^2
- Generalized Structure Functions ($\Rightarrow$ GPD)

CEBAF concept and performances





Recirculation Arcs (N=1-5 passes)

- ☞ 2 LINAC of 0.6 GeV max.
- 3 beams simultaneously
  - Choice of E ($N \times E_0$ (1 pass)) and Intensity for each Hall
- Emittance $\approx 2\ 10^{-9}$ m.rd
- Resolution in energy $\delta p/p < 10^{-4}$

Supraconducting cavities

- 100 μA (1MW with e^- of 4 GeV)
  - Cycle utile de 100% (2 ns structure, pulse <100ps)
- Cryomodules JLab (340, $\approx$ 8 MV/m)
  - ☞ 4 GeV (planned) → 6 GeV
  - ☞ New modules (12 MV/m)

Interaction de couleur

Confinement

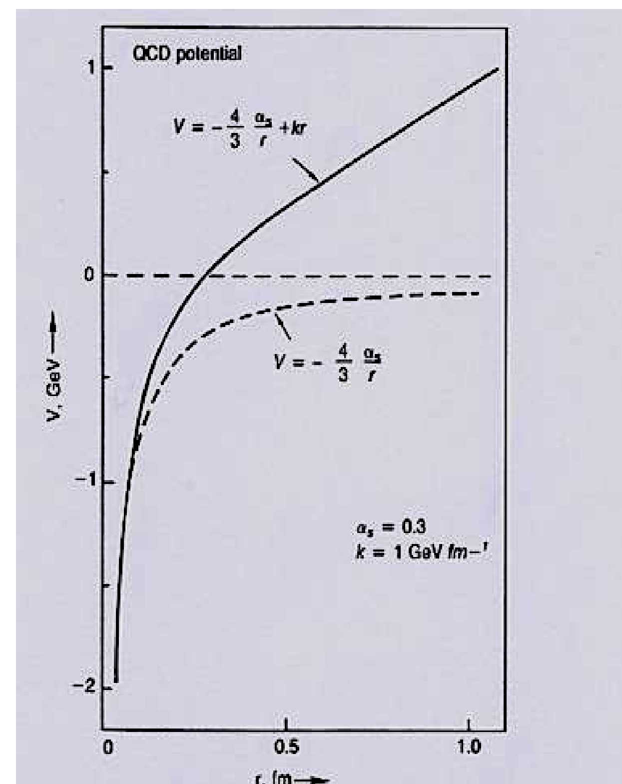
- Etats propres de SU(3) : Singulets de couleur
  - ☞ quarks ou gluons ne peuvent être observés seuls/libre

Force quark-quark

- Echange des couleurs via des gluons (8) colorés (couleur + anticouleur)
  - Gluons interagissent entre eux (diagrammes à 3-4 gluons)
- Echange d'un gluon : Force attractive pour les états singulets de couleur

2 régimes distincts

- A petite distance
  - ➲ Liberté asymptotique (V_{q-q} (forte) $\rightarrow$ 0)
- A grande distance, V augmente (en kr)
  - Augmentation charge couleur (gluons)
  - Création paires quark-antiquark



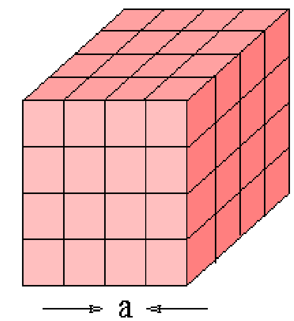
Form of the QCD potential $V = -\frac{4}{3}(\alpha_s/r) + kr$, with $\alpha_s = 0.3$ and $k = 1$ GeV fm^{-1}.

QCD sur Réseau

Calcul de théorie des champs

- Lagrangien physique (QCD, ...)
- Discrétisation de l'espace temps (x,y,z,t)
  - $a^3.n_t$ (10^6) sites où l'on calcule le champ
  - Variation (MC) des valeurs de champ
    ↳ erreur statistique
- Intégrales sur toutes les configurations (10^4)
  ↳ Observables (masses ...)

Pour chaque bin en temps !



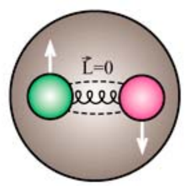
Hypothèse/simplifications

- Maille élémentaire finie ($a \neq 0$)
- Volume fini (conditions aux limites)
  ↳ Erreurs systématiques
- Métrique (Minkowski $\rightarrow$ Euclidien)
  ☞ Pas adaptée pour les états de diffusion
- Approximation "quenched"
  (gluons mais pas de boucles (paires))
  ☞ prédictions pour mer qq ??

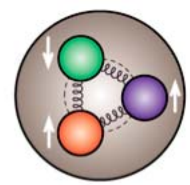
Prédictions

- Progrès avec techniques de calcul
- Masses hadrons à 10%
- Masses quarks constituants, interaction q-q
- Constantes faibles, CKM
- ... toutes théories des champs

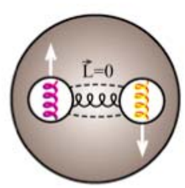
QCD



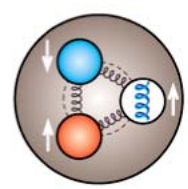
Meson ($q\bar{q}$)



Baryon (qqq)



Glueball (gg)



Hybrid ($q\bar{q}g$)